AN INNOVATIVE APPROACH TO ASSESS QUANTITY-DISTANCE

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ABSTRACT

Protection of personnel, properties, and equipments is the main concern to the Air Force and other DOD agencies for their ammunition storage program. The review of the available reports and standards , documented on assessment of hazards associated with a given situation, lead to identification of five principal effects (DOD 6055.9 STD); namely: (1) blast pressure, (2) primary and secondary fragments, (3) thermal hazards, (4) chemical hazards, and (5) ground shocks. Extensive studies have been performed in the past on hazardous effects of blast pressure, induced thermal and chemical environments, and ground shocks. However, the degree and extent of fragment induced hazards associated with accidental detonation of explosives stored in rock/soil structures (underground chambers) are still not fully verified. The empirical relationships used are too general and do not account for site specific characteristics of the geologic system (rock and/or soil mass) and engineering system (structural components). The results of a recent KLOTZ tunnel explosion test, conducted at China Lake, California confirmed the importance of rock mass characteristics, natural joints, and concrete support (hardness elements) on the generated fragments (Bakhtar, 1989). Based on the limited test conducted, it is clear that additional research is needed to develop more accurate Q-D relationships which accounts for site specific properties of the host media, structure, and the quantity of explosive stored. This paper describes the general formulation of an innovative approach for quantity-distance assessment which accounts for the site specific properties of the underground structure (engineering system) and the characteristics of the geologic formation hosting the subsurface facility. The functional form of a recently developed Q-D criteria is presented along with the procedural details for verification. Finally, applications of physical modeling under normal gravity, with emphasis on modeling tunnel explosion scenario, are discussed which will provide a cost-effective approach for model testing and research in the area of explosive hazard prediction.

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BACKGROUND

Studies relative to explosive safety quantity-distance (Q-D) effects from detonations of shallow underground magazines in hard rocks have been underway since early 1970. The overall objectives of the test program are to determine the hazardous effects of; tunnel/chamber blast pressure, free-field air blast, free-field ground motion, and ejecta/debris produced by accidental detonation of explosive magazines which rupture the overhead cover of the underground chamber. Many empirical relationships have been developed, based on data from near surface bursts, to determine the free-field air blast pressure and induced ground motion. However, estimates of the debris thrown and the associated kinetic energy are much harder to make in the absence of detailed information on site specific rock mass characteristics.

In order to study the explosive safety quantity-distance, a shallow underground tunnel/chamber explosion test (KLOTZ Tunnel) was performed at the Naval Weapons Center in China lake, California , on August 24, 19988. The test consisted of a 20,000 kg (44,000 lbs.) -- net explosive weight -- detonation inside a half-scale tunnel/chamber system constructed in highly weathered granitic rock mass. Prior to shotcreting and emplacement of explosives, a detailed rock mass characterization was performed in the tunnel and attached chamber and relevant geologic and geo-engineering information were documented (Bakhtar, 1988).

Based on the pre-blast rock mass characterization, five major joint sets and a single shear zone were identified within the site. The major joint sets were blocky with well defined dip/strike and spacings. The block sizes were generally 0.43 m (17 in) to 0.56 m (22 in) in length. The Q System developed by Barton et al. (1974) was employed for rock mass characterization. Values of 0.65 and 1.3 were obtained for the tunnel and chamber, respectively, which categorized the rock from "very poor" to "poor" on the basis of the Q System. Seismic wave measurements and index test performed in situ indicated that unconfined compressive strength of the rocks was much less than expected because of extensive weathering.

Post-blast analysis of rock mass, reported by Bakhtar (1989), based on visual observation at the site revealed the following:

- - Larger ejecta were from the jointed blocky rocks.
- - The intact rocks with minor random joints were broken into smaller pieces in comparison with those from major joint sets.

- The majority of pieces (ejecta) observed around the test site with at least one smooth-weathered face (originated from major joint sets) were smaller than 0.43 m x 0.43 m x 0.30 m (17 in x 17 in x 12 in) in size.

- The majority of pieces (ejecta) observed around the test site from intact rock were less than 0.25 m x 0.25 m x 0.38 m (10 in x 10 in x 15 in) in size.

- Broken rocks (ejecta) were observed beyond 300 m (982 ft) line from the original location of the portal.

- Large pieces of concrete (debris) 0.97 m x 0.79 m x 0.38 m (38 in x 31 in x 15 in) thrown more than 61 m (200 ft) from the original portal location.

- The sizes of ejecta thrown originating from the jointed rocks were larger than those from the intact rocks.

- Higher kinetic energy associated with ejecta originating from joint sets than those from intact rocks.

The results of above observation indicate the importance of site characterization, identification of major geological features, and an understanding of the basic mechanical/physical properties of rocks hosting the underground explosive structures.

Data obtained from the KLOTZ Tunnel explosion test in China Lake, California, provide a unique opportunity to physically construct a series of scale model experiments to validate a more precise "scaling law" for the current Q-D standards for underground storage of munitions. This paper outlines the results of a recent feasibility study completed on development of a novel approach for assessment of quantity-distance based on an empirical relationship which accounts for the characteristics of the geologic and engineering systems in addition to the chamber loading density. Furthermore, it elaborates on the uniqueness of using scale model testing under normal gravity for validation and verification of the explosive safety standards. The physical modeling approach is particularly attractive because prototype scenario can be modeled at a small scale at a fraction of the cost. Assuming the similitude conditions are preserved, the results from the scale model tests can be used to predict prototype behavior. Additionally, the geologic and engineering systems are physically modeled and test are performed under pre-determined controlled conditions which facilitate the ease of instrumentation and retrieval of maximum information.

PHYSICAL MODELING CONCEPT

Traditionally, munitions have always been stored in underground structures. Several of the existing US and NATO facilities were built many decades ago and in part have undergone extensive weathering and deteriorations. With the growth of population, personnel safety issues around these facilities are of the main concern to the Air Force and other DOD agencies. Therefore, the need for economical techniques to evaluate the performance, in particular load response resulting from internal detonation, of these structures is growing. The full-scale structures designed in geologic materials can not be tested for their load response. Even if the possibility of such tests existed, i.e., KLOTZ Tunnel explosion test in China Lake, California, it would involve extensive instrumentation scheme, high capital expenditures, in addition to planing and communication difficulties which always exists because of large geographic distances separating the responsible individuals in charge.

The difficulties encountered in testing full scale (prototype) structures warrant the need for scale models in which the linear dimension, or geometry, of the prototype structure is reduced by a certain definite scale. Because the geometry is scale down, the strength-related parameters also need to be scaled down in order to maintain dimensional homogeneity between a prototype structure and its model. The design of synthetic geologic materials, herein called "rock simulant," for scaled model testing therefore needs to be done in such a way that similarity in material behavior (i.e., prototype/model behavior) is conserved and the important dimensionless strength related ratios remain unchanged for the model and prototype.

For geologic materials scaling affects the material behavior, particularly, the overall strength. Other features of the geologic materials that may affect the behavior of full scale structures are discontinuities and unconformities. These need to be accounted for in physical modeling. In general the choice of the model depends on

- - nature of investigation
- - limitation of testing facility
- - economic constraints.

In order to model, within an acceptable approximation, a particular geology with associated discontinuities at the reduced scale, the proper ingredients need to be mixed in appropriate portions to produce low strength "rock-like" materials. Because no standard low-strength rock simulant exist, the method developed by Bakhtar (1984) and described in details by Bakhtar (1986, 1987) may be employed to identify and formulate

low strength synthetic geologic materials which have dimensionless strength related properties similar to those of rocks. It is important to note that feasibility of scale-model testing based on material scaling developed by the author for underground structures have been proven through a decade of research sponsored by the Defense Nuclear Agency (DNA).

In general, tests on reduced scale models are based on the possibility of changing the three scales of length, time, and force (or mass) without altering the equations describing a mechanics phenomenon. The model material should exhibit rock-like behavior beyond elastic limit, i.e., considerations of both linear and non-linear requirements. The model materials should be chosen in such a way that their elastic, inelastic, plastic, and viscous behavior are similar to rock response at reduced scale. Also, density and dilatational wave velocity (characteristic impedance of the medium) are important intrinsic material properties under blast loading conditions and must be accounted for in modeling under normal gravity.

The complete similitude for formulation and fabrication of material model (rock-simulant) would require the following conditions to be satisfied:

$$(\sigma_c/E)_{prototype} = (\sigma_c/E)_{model} \tag{1}$$

$$\upsilon_{prototype} = \upsilon_{model} \tag{2}$$

$$\phi_{prototype} = \phi_{model} \tag{3}$$

where:

σ_c = unconfined compressive strength

E = Young's modulus

υ and ϕ = Poisson's ratio and angle of internal friction, respectively.

An extensive report outlining the scaling relationships and applications of scale model testing to underground structures is being prepared (Bakhtar, 1992) and will be submitted to the United States Air Force under SBIR Phase II research program for publication in October. This report elaborates on the scaling laws under normal gravity and provides

a systematic procedure for prediction of the prototype response based on model behavior.

By and large, for static problems only two fundamental quantities are involved: force (F) and linear dimension (d). For dynamic problems, such as blast loading, The scaling laws that govern the dynamic relationship between a model and its prototype depend on the geometric and material properties of the structure and the type of loading. The derivations of these relationship have been presented in a recent report Bakhtar (1991) and are elaborated in detail by Bakhtar (1992, under press). Generally speaking, the dynamics of any structure are governed by an equilibrium balance of the time-dependent external forces that are the product of local mass and acceleration, the resistance forces that are a function of stiffness of the soil and rock/structure in the particular direction in which motion is occurring, and the energy dissipation of the damping forces, whether material or construction related. For the tunnel explosion test scenario, i.e. China Lake KLOTZ Tunnel, following detonation, the blast and gas induced energy go into internally pressuring the chamber and access tunnel and eventually breaking the rock cover and creation of the crater before damping forces are activated.

By far, the most important step in physical modeling of the geologic materials is the identification of the pertinent parameters which need to be accounted for (Bakhtar and DiBona, 1985; Bakhtar and Jones, 1986). For cases of interest to us, these parameters include:

- Elastic properties (Young's modulus and Poisson's ratio)
- Triaxial shear strength
- Unconfined strength characteristics
- Angle of internal friction
- Density
- Impedance characteristics
- Frictional characteristics of joints and discontinuities

BAKHTAR'S Q-D FORMULATION

GENERAL

The peak pressure associated with detonation of a partially confined source , i.e, explosives stored in an underground structure is initially extremely high and becomes amplified by reflection within the chamber. In the absence of adequate venting, the explosive induced gases exert additional pressure and the combined effects increase the duration of loading and may result in eventual destruction of the structure. At the beginning of this paper, the five principal effects that are associated with the accidental detonation of a storage magazine were outlined. The thrust of this paper is the rational behind development of an explosive safety criteria by considering the hazards associated with the impact energy of explosion induced fragments.

The Air Force Explosives and Safety Standards (1990) and the Department of Defense Ammunition and Safety Standards (1984) define fragments as primary or secondary depending on their origins. Primary fragments are formed as a result of shattering the explosive casing or container, they are usually small, and travel initially at velocities of the order of thousands of feet per second. Secondary fragments are formed as a result of high blast pressure on the structural components, they are larger in size than primary fragments, and travel initially at velocities in the order of hundreds of feet per second. The DOD Standards further defines a hazard fragment as one having an impact energy of 58 ft-lb (79 joules) or greater.

The damage or injury potential of explosion induced fragments is normally determined by the distance prevailing between the "potential explosion site" (PES) and the "exposed site" (ES), DOD6055.9 STD, and

i) ability of PES to suppress the blast overpressure;

ii) ability of ES to resist the explosion effects.

The available Q-D relationships were established for related and unrelated PES and explosives, explosives and nonexplosive ESs. For explosives stored in facilities constructed in rocks, the current Q-D relationships are based on cubic-root expressions having a general form:

$$D = KW^{1/3} \tag{4}$$

where:

D - distance (ft),
W - weight of explosives (lb),
K - risk factor.

The review of available documents on explosive safety and the results of rock mechanics investigation at the tunnel explosion test site (Bakhtar, 1989) reveal the influence of rock mass characteristics, loading density, structural hardness, and venting characteristics of the system, in determination of the quantity-distance and safety criteria for the underground explosive storage structures.

RATIONALE

The phenomenology of explosive effects in hard rocks, explosive hardening and survivability of shallow tunnels comprising potential explosion sites; such as munitions storage chambers; are very much affected by the hardness or "equivalent stiffness" (overall rock mass deformability modulus) characteristics of the geologic units hosting the structures. The equivalent stiffness characteristics of the geologic units, in turn, are dependent on:

- size of individual rock blocks between joints
- joint roughness and dilation
- extent of weathering
- degree of saturation
- in situ stress field
- physical and mechanical properties of rock mass
- seismic (also called sound) wave velocity.

In developing safety criteria for the explosive storage structures in rocks, all the above parameters should be included in order to realistically account for the overall characteristics of the geologic system. Additionally, the characteristics of the engineering system, i.e., structural components should be accounted for.

The underground explosive storage structures constructed and/or planned for construction by the United States Air Force and other government agencies do not have the benefit of performance monitoring. Safety requirements are nevertheless dictated by the Q-D standards for the allowable quantity of explosives to be stored. In the absence of site specific information on the characteristics of engineering and geologic systems, no matter

what quantity of explosive is stored in an underground chamber, the safety specialists (engineers) will come back to the basic question-- "How much damage is to be expected to the exposed site (ES) in case of accidental detonation of the potential explosion site (PES)?"

At present, the Q-D relationships, similar to Equation 4, are used to determine the safe distance around a potential explosion site. However, as evident from the recent tunnel explosion test in China Lake, the site specific characteristics of the storage structure (engineering system) and the host medium (geologic system) play dominant roles in assessment of hazardous effect of the fragments generated by the explosion. Furthermore, the joints or discontinuities control the propagation of the ground shock and the kinematics of the resulting motion, as observed around many nuclear and high explosive (HE) tests (Bedsun, et.al., 1985). Therefore, an explosive safety criteria which accounts not only for the loading density, but for the pertinent site specific characteristics of the geologic and the engineering components of the storage magazines is required to provide the necessary protection for personnel and property. The Bakhtar's Explosive Safety Criteria was formulated to account for the pertinent and site specific characteristics of ammunition storage structures and may provide much more accurate approach than the available techniques.

FORMULATION OF EXPLOSIVE SAFETY CRITERIA

As mentioned previously, development of a reliable safety criteria is contingent on the ability to characterize and assess the equivalent stiffness characteristics of the engineering and geologic systems. These requirements present a challenging task for engineering planning. The varied properties of adjacent rocks, both in terms of hydrology and deformability, lend emphasis to the importance of reliable extrapolation procedures.

The site specific features which will provide the principal challenge in the assessment of the equivalent stiffness characteristics of rock mass hosting an explosive storage chamber are:

- extent of discontinuities or simply "joints"
- number of joint sets
- amount of water or degree of saturation
- various adverse features associated with loosening, high stress, squeezing and swelling
- strength of intact rocks
- shear and normal stiffness of joints, or simply shear strength.

Also, important characteristics of the engineering system, i.e., the structural components, which include:

- loading density
- stiffness characteristics
- venting characteristics (number of entrances).

The Bakhtar's formulation of the explosive safety criteria combines the above parameters into a single functional empirical expression with the following general form:

$$D = f(E^a,\ L^b,\ R^C,\ V^d,\ S^e) \tag{5}$$

where:

D = distance, m (ft) ;

E = equivalent stiffness defining characteristics of geologic system, GPa (psi);

L = loading density, kg/m^3 (lb/ft^3) ;

R = equivalent stiffness defining characteristics of engineering system, GPa (psi);

V = P-wave velocity in geologic system, m/sec (ft/sec);

S = venting characteristics of the engineering system, m^2 (ft^2).

a, b, c, d, e = constants.

The five parameters chosen to describe the Bakhtar's formulation, Equation (5), are easily obtained in the field as briefly described in the following pages. More detailed information on the rock mass characterization can be found by referring to the final report on the China Lake Tunnel Explosion Test (Bakhtar 1988, 1989).

EQUIVALENT STIFFNESS OF ROCK MASS

The equivalent stiffness, or the overall deformation modulus, of the rock mass is determined based on the Q-system of rock mass classification developed by Barton, et.al., (1974). In the Q-system, six parameters are chosen to describe the rock mass quality in the following way:

$$Q = \left(\frac{RQD}{J_n}\right) \cdot \left(\frac{J_r}{J_a}\right) \cdot \left(\frac{J_w}{SRF}\right) \tag{6}$$

where:

RQD	=	rock quality designation (Deere, 1963)
J_n	=	joint set number
J_r	=	joint roughness number (of least favorable discontinuity or (joint set))
J_a	=	joint alteration number
J_w	=	joint water reduction factor
SRF	=	stress reduction factor

It is important to notice the values J_r and J_a relate to that joint set or discontinuity most likely to allow initiation of failure. The important influence of orientation relative to the tunnel axis is implicit.

Detailed descriptions of the six parameters and their numerical ratings are shown in publications by Barton and presented in a recently completed work by Bakhtar (1991) for the United States Air Force under the SBIR Program. The range of possible Q values (approximately 0.001 to 1000) encompasses the whole spectrum of rock mass qualities from heavy squeezing ground to sound unjointed rock. Figure 1 shows how the rock quality and support requirements are determined based on the Q values.

RQD (Rock Quality Designation)

RQD is based on a modified core recovery procedure. This, in turn, is indirectly based on the number of fractures and amount of softening or alteration in the rock mass as observed in the rock cores from a drill hole. Instead of counting the fractures, an indirect measure is obtained by summing up the total lengths of core recovered, but counting only those pieces of core which are 10 cm (4 inches) in length, or longer, and which are hard and sound (Deere, 1963). In the absence of drilled cores, the method is applied directly to the excavated walls.

Joint Roughness (J_r)

Joint roughness, most commonly found in rocks, ranges from 1.0 to 20, which represent smooth-planar, rough-planar and smooth-undulating surfaces, respectively. Extreme values may consist of discontinuous joints in massive rock and plane slickenside surfaces typically seen in faulted rock and in clay fillings. It is measured using a profile gauge.

Joint Alteration (J_a)

The joint alteration parameter describes the conditions of joint in fillings. It can describe the unaltered or unweathered joint, or as is most commonly seen, clay minerals of various kinds. Favorable cases include the joints which are healed.

Joint Water (J_w)

The joints water-reduction factor describes the degree of water inflow and is strongly biased in the direction of "dry excavations or minor inflows" (less than five liters per minute locally).

Stress Reduction Factor (SRF)

The stress reduction factor has 16 classes, which are divided into four broad groups:

1) Weakness zones causing loosening or fall-out.
2) Rock stress problems in competent rock.
3) Squeezing-flow of incompetent rock.
4) Swelling chemical effects due to water uptake

Group (1) refers to cases where the infillings are the direct cause of loosening and fall-out.

Rock stress problem arises when the ratio of σ_c/σ_1 is less than 10.

Equivalent Stiffness or Modulus of Deformability

Estimates for range of deformation modulus are made on the compilation of in situ test data by Barton (1980) and Bieniawski (1974). Large-sale deformation modulus measurements that have been correlated with Bieniawski's (1974) RMR rock mass quality ratings are shown in Figure 2. The relationship between RMR and Q values were obtained by Bieniawski. As shown in the Figure, the approximate lower and upper bond values of modulus are given by **[10 logQ]** and **[40 logQ]** for Q values larger than 1. The filled circles in Figure 2 are values that have been correlated with Q values by Barton, et al. (1982).

Remarks on Rock Mass characterization

The pertinent parameters required for determining "Q" using Equation (6) are obtained based on simple index testing in the field. Typical example is the KLOTZ Tunnel rock mass characterization which was reported by Bakhtar (1988, 1989). Tables providing numerical ratings for the various parameters defined in the Equation (6) are available which facilitate the ease of characterization (Barton et al., 1974).

LOADING DENSITY

The loading density is defined as the ratio of net explosive weight to the volume of the chamber. If the overall loading density is required the volume of the access tunnel is added to the chamber volume. In the Bakhtar's formulation, Equation (5), the chamber volume is considered for calculation of the loading density.

EQUIVALENT STIFFNESS (CHARACTERISTICS OF ENGINEERING SYSTEM)

The equivalent stiffness of the engineering system defines the hardness characteristics of the structure and can be determined as the overall deformability modulus. It can be determined in the field using a Schmidt Hammer technique.

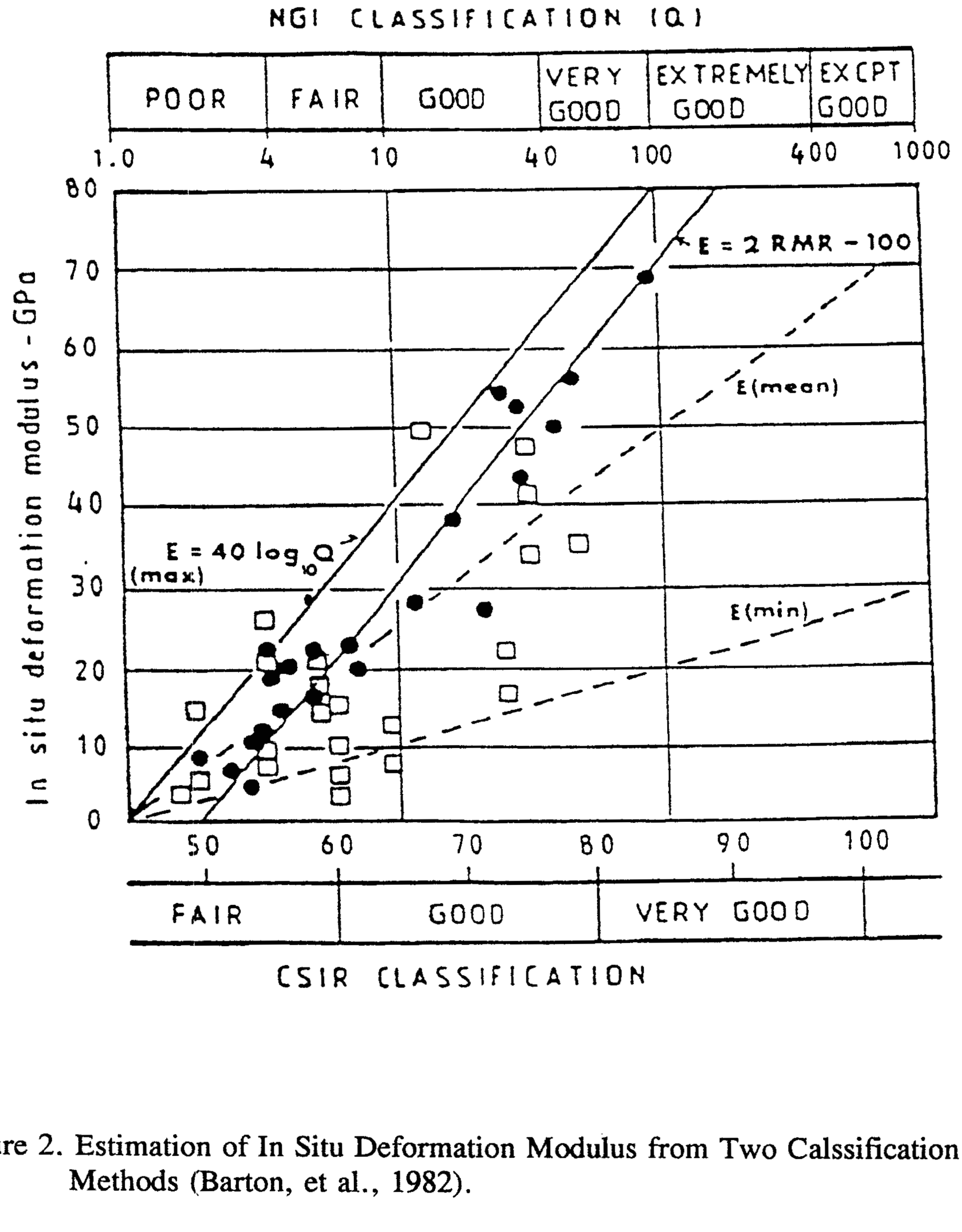

Figure 2. Estimation of In Situ Deformation Modulus from Two Calssification Methods (Barton, et al., 1982).

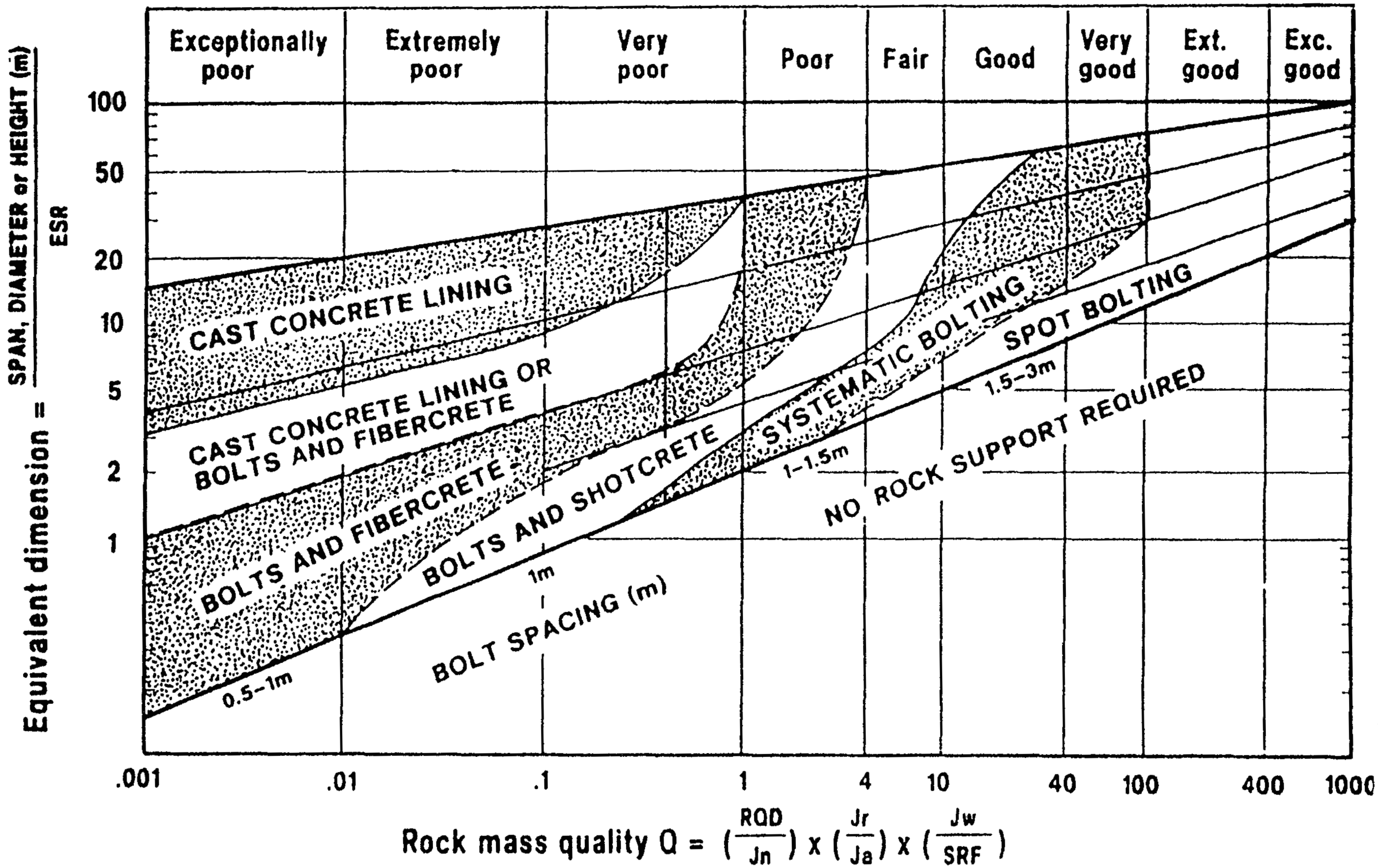

Figure 1. Two Hundred Case Records Plotted in Terms of Rock Quality and Excavation Dimensions. These Cases Form the Basis for Support Selection (Barton, et al., 1974).

P-WAVE VELOCITY

The P-wave or seismic wave velocity through the geologic formation is the most important intrinsic material property that can be determined in the field which defines the site specific characteristics of the geologic system. The seismic wave velocity can be estimated based on the rock quality (Q) using the relationship developed by Bakhtar (1992) which eliminates the need for the field measurement.

VENTING CHARACTERISTICS

Venting characteristics refer to the average cross-sectional areas of the openings. For the case of chamber with one access tunnel venting characteristics, the term "S" in Equation (5), represents the average sectional area of the tunnel. Chambers with two or more access tunnels, summation for the average sectional areas representing each single opening should be accounted for.

DIMENSIONAL ANALYSIS

The functional relationship shown in Equation (5) can be solved using dimensional analysis which yields an expression of the following form:

$$D = g[(E)^{-(0.5 + b)}(L)^{b}(R)^{(0.5}(V)^{2b} (S)^{0.5}] \tag{7}$$

where: g and b are constants which can be determined from scale model testing, physical modeling at normal gravity.

It should be noted that the functional relationship shown by the Equation (5) represent the general form of the Bakhtar's explosive Safety Criteria. The terms shown in the expression (5) are the constituent parameters representative of the site conditions and are determined based on index testing. Dimensional analysis was used to determine the possible variations of the Equation (5) and expression shown by the Equation (7) was derived. However, the final form of the Bakhtar's explosive safety criteria for underground structures will be verified following the completion of a series of scale model tests planned (Air Force SBIR Phase II) during the Fiscal Year of 1993.

PHYSICAL SIMULATION OF TUNNEL EXPLOSION TEST

Applications of numerical and physical modeling for event simulation are commonly practiced in engineering and physics. Physical modeling has the advantage that a correctly constructed dynamic scale model shows a behavioral response which simulate exactly that of the prototype at a smaller scale. Therefore, scale model tests, assuming correctly constructed, in majority of cases can be used to predict the prototype behavior and assist in verification of numerical models. For blast loading, both geometric and kinematic similarity between the model and prototype structures must be satisfied for realistic simulation.

For modeling structures in rock mass **(also applies to hardened aircraft shelters)**, the following basic conditions of similarity must be satisfied:

- **Geometric Similarity** - requires the ratio of distances between any two points in prototype to the corresponding distances in its model to be constant.
- **Kinematic Similarity** - requires that the movement of the particles in the model follow those of its prototype with respect to time and space.

Geometrically and kinematically similar structures are dynamically similar if the ratio of various similar mechanical forces that act on any two corresponding particles in the prototype and its model are constant. Assuming F^* is the force scale factor (ratio of force in the prototype to that in its model), the above conditions can be mathematically represented by:

$$\frac{(F_g)_m}{(F_g)_p} = \frac{(F_i)_m}{(F_i)_p} = \frac{(F_v)_m}{(F_v)_p} = \frac{(F_e)_m}{(F_e)_p} = \frac{(F_f)_m}{(F_f)_p} = F^* \qquad (8)$$

where:

F_g = gravity force
F_i = inertia force
F_v = viscous force
F_e = elastic forces
F_f = friction force
Subscripts m and p refer to model and prototype, respectively.

The size and material properties of the model, with all the structural components,

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can be determined based on the following relationship:

$$\sigma^* = l^* \rho^* \tag{9}$$

where:

σ^* = stress and/or strength scale factor = σ_p / σ_m
l^* = geometric scale factor = l_p / l_m
ρ^* = density scale factor = ρ_p / ρ_m

Using equations (8) and (9) the majority of scale factors needed for model studies can be derived (Bakhtar, 1991, 1992). Several of those scale factors are shown in the Table 1.

In order to verify the explosive safety criteria discussed above for the underground storage structures and the associated Q-D standard, Equation (9) is used to design and fabricate a series of scale model experiments. Figure 3 shows a schematic of a typical test bed which will be embedded within a geologic formation with matched impedance characteristics. The China Lake KLOTZ tunnel explosion scenario is used as the prototype and the results of rock mass characterization performed by Bakhtar (1989) are used to derive the relevant scale factors.

The above mentioned tests provide the necessary data for verification of the scaling relationships developed (Bakhtar, 1992) for internal detonation within a shallow structure and final formulation of the Bakhtar's explosive safety criteria represented by the Equation (5).

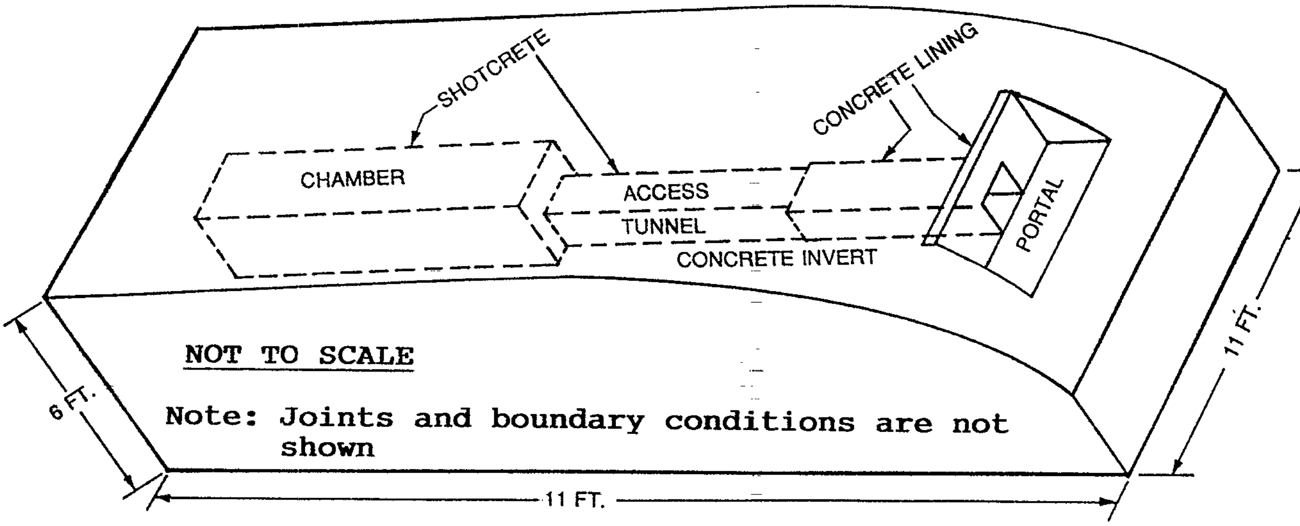

Figure 3. Schematic of a Typical Test Bed

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Table* 1 - Scale Factors for Mechanical Quantities

Quantity	Dimensional Form	Scale Factor
Linear Dimension	L	1
Area	L^2	l^{*2}
Volume	L^3	l^{*3}
Density	ML^{-3}	$m^* l^{*-3}$
Time	T	$l^{*1/2}$
Stress	$ML^{-1}T^{-2}$	$m^* l^{*-2} = m^* l^{*-1} t^{*-2}$
Force	MLT^{-2}	$m^* l^* t^{*-2} = m^*$
Velocity	LT^{-1}	$l^{*1/2}$
Acceleration	LT^{-2}	$l^* t^{*-2}$
Angular Velocity	T^{-1}	t^{*-1}
Mass	M	$\rho^* l^{*3}$
Energy	MLT^{-2}	$m^* l^* t^{*-2}$
Impulse	MLT^{-1}	$m^* l^* t^{*-1}$
Strain	LL^{-1}	1
Friction Angle	L^O	1
Poisson's Ratio	$\Delta l_1/L_1/\Delta l_2/L_2$	1
Frequency	T^{-1}	t^{*-1}
Curvature	L^{-1}	l^{*-1}

* - references: Bakhtar 1991 and Bakhtar 1992

The above relationships should be satisfied for any surface or subsurface structures

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REMARKS

It is firmly believed that successful completion of a correctly constructed scale model test program can contribute towards several areas of interest to prediction of hazardous effects of explosives. The finalizing remarks presented in this section highlight several areas which can be covered under the scale model testing.

Verification and optimization of a more complete Safety Criteria - properly scaled model structures can be used to verify a well formulated and generalized explosive safety criteria for munitions magazines constructed in geological formations. Equation (5), presented earlier, is an example of such formulation which accounts in addition to the loading density of the explosive storage structure for the site specific characteristics of geologic (rock/soil mass hosting the underground facility) and engineering (structural components) systems. Once the pertinent parameters of interest for scenario verification are identified, the scale models can be constructed and tested at fraction of cost for prototype structures. A series of such tests are planned for the United States Air Force in Fiscal Year 1993 to verify the functional relationship, Equation (5), developed by Bakhtar (1991). The main ingredients for model fabrication consist of barite, bentonite, glass beads, an air entraining agent, Portland Cement Type I and II, and water.

Important applications of the empirical relationship derived by Bakhtar (1991), expected to complete the verification based on scale model testing, for underground explosive storage structures are listed below:

- Verification of a more precise safety criteria which can be introduced into the current Q-D standards.

- Determination of the "optimum load," (unique approach) i.e., the loading density that upon accidental detonation causes localized repairable internal structural damage to the chamber without damaging the structural integrity of the cover rock or the access tunnel.

- Determination of communication between adjacent magazines in case of accidental detonation in one chamber and optimization of loading density.

- Determination of the required depth of cover for a given storage

structure and optimization of loading density.

- Verification of numerical models.

- Site characterization.

- Classification and loading density optimization of existing underground magazines.

- Safe design of next generation magazines.

Studies related to movement of blast-induced fragments - a detailed study of the movement of blast-induced fragments based on prototype structures is very difficult to conduct because of the following reason:

- Detonation within geologic formation crushes the soil and rocks into fragments of different sizes, ranging from specks of dust to very large fragments several meters in size. In addition, the shape of the fragments generated differ greatly (Baron, 1960). Because the extent of retarding force in the air depends on the shape and mass of the fragment (ejecta and debris), it becomes very difficult to calculate the air drag for an entire mass of ejecta originating from a prototype explosion because of wide range of fragment breakages and uncertainty of fragment shape. Therefore other simplified means which the characteristics of the test beds, initial conditions, can be determined and defined prior to detonation are needed.

- The initial projection velocity of ejecta can not be determined with adequate accuracy. Although currently fast-frame (still and movie) cameras are used, also, there are formulas available for calculating the initial velocity of projection, they only hold good for the **throw-front**. Velocity of ejecta behind the throw-front vary over a long range. Errors in evaluating the initial velocity leads to wide errors in calculating the quantity-distance. For example, if the initial velocity of projection is known within $\pm 10\%$ accuracy, it leads to an error of $\pm 20\%$ in the estimated value of the range of scatter in a case of very large fragments.

- Ejecta moving in the air collide with one another. As a result the

velocity changes drastically in magnitude and direction. Beside interference on the nature of movement is observed when ejecta move in the form of a solid mass. Large perturbations are caused by the bursting out of explosion products which are ejected at a velocity considerably greater than the velocity of individual ejecta. The explosion products impart a very high velocity to the ejecta emerging along with them. As a result a cloud of fast-flying fragments is formed in the front of the main mass of exploded rock. This phenomenon was clearly observed during the KLOTZ Tunnel explosion test in China Lake, California. Therefore, basic understanding of hazardous effects resulting from movement of blast induced fragments can best be achieved if the initial conditions are known and test are conducted under controlled boundary constraints.

- The air between ejecta moving at short distances from each other is also set in motion which considerably changes the initial flying conditions and interaction with the medium and other fragments. In particular, as observed from high-speed photography, a continuous stream of soil is usually divided into a number of cone-shaped jets, some of which move well ahead of the main body of ejecta. A theoretical investigation of this process was first undertaken by Professor Pokrovskii (1959).

Therefore, it is clear that the main problem in determining the constitutive laws of movement of a body, originating from the surface or below the surface, projected in the air (ballistics) can not be formulated without a stagewise division in order to simplify the process of detonation by reducing the yield or net weight of explosive. Clearly, the scale model testing based on physical modeling under 1-g provides an attractive alternative to support such studies.

<u>**Studies to formulate laws of ejecta distribution**</u> - detailed studies on distribution of ejecta resulting from internal detonation within a volume of a rock mass can lead to refinement of the Q-D standards. For hazardous effects prediction, it is very important to know the expected value of a fragment size and the ejecta frequency distribution based on loading density. It is important to develop a localized constitutive law providing the density of distribution of rock in fractions which shows which part of the ejecta belongs to the fraction measuring d_f per unit volume. Where d_f is the relative size of the ejecta normalized with respect to the largest fragment. Development of such localized constitutive laws of frequency

distribution is contingent on our ability to completely characterize the rock mass to determine the nature of distribution of discontinuities for the medium which is being fragmented. Since the rock mass characteristics and conditions are not controlled by a definite constitutive relationship and as previously mentioned are site specific, the localized constitutive laws of distribution can only be determined by experiments using scale modeling techniques. For such purposes methods of concentric layers of colored rock-simulants can be employed to cast the model.

In addition, to calculate the differential law of ejecta distribution, i.e., the mathematical expression that predicts the probable maximum and average size of ejecta based on a given loading density, it is necessary to know the localized and site specific or initial PES conditions. The simplest approach for formulating a generalized differential law of distribution is the scale model testing. For such scale model tests it is necessary to use same rock-like materials within which the explosion is conducted and preserving the geometric and kinematic similarity of charges and volume of the material to be blasted.

Based on the discussion presented above it is clear that physical modeling technique, using scaled materials can open a full spectrum of opportunities in studies related to "explosive hazards reduction".

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